ATV SEPARATION AND DEPARTURE STRATEGY FROM UNCONTROLLED INTERNATIONAL SPACE STATION

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ABSTRACT

The Automated Transfer Vehicle (ATV) is an unmanned cargo vehicle developed under European Space Agency (ESA) contract by EADS Space Transportation as prime contractor, to be part of the European contribution to the ISS (International Space Station) program.

One of the main issues of the ATV flight scenarios design is the ISS safety in case of contingency. In some cases, it has been necessary to design specific scenarios dedicated to particular off-nominal situations.

This paper presents a strategy that has been elaborated to ensure a safe departure in response to an emergency case where the ATV is captured by the Russian docking port but the docking mechanism cannot be rigidly locked and therefore attitude control of the ISS cannot be reactivated.

We will first define the initial conditions at departure by analyzing ISS motion during the attached phase and its consequences in terms of communication unavailability with the Ground. These elements will enlighten the design of the separation and departure strategies that will be themselves successively defined. The safety of the resulting trajectories will at last be described.

1. ATTACHED PHASE BEFORE DEPARTURE

1.1 Uncontrolled ISS motion

During docking operations, the International Space Station (ISS) attitude remains uncontrolled from the first contact between the Automated Transfer Vehicle (ATV) probe head and the docking mechanism until a successful diagnosis of the docking is performed. This aims to limit the loads applied on the probe head before its complete retraction and to avoid the risk of excitation of oscillating modes at ISS nodes.

Here, we consider a contingency case where only the probe head is captured but the ATV is not rigidly locked into the docking mechanism. In this situation, no positive diagnosis can be done and the ISS can not recover controlled mode before a solution has been found for the vehicle to be separated and to free the station vicinity. Some time is needed (probably more than 20 minutes) to get confirmation that the docking has failed, to be sure that there remains no chance to complete it, and to take the departure decision. But in order to get the problem fixed within the next Russian ground stations visibility slot (during the following revolution, since the docking occurs already above Russia), the departure must be effective within 110 minutes following the uncompleted capture.

During this time, the ISS does not remain in a constant attitude due to its initial motion before contact and to the torque created by the docking impulse, the gravity gradient, the aerodynamic forces (negligible here) as well as the gyroscopic torque. No control torque is applied since the ISS is in free drift attitude.

The initial attitude rate just before contact is specified to be within 0.02 °/s on each axis (pitch, yaw, roll) and the initial ISS attitude is specified to be within 3.4 ° per axis from the nominal Local Vertical Local Horizontal (LVLH) attitude.

The docking impulse is due to the transfer of energy from the ATV to the ISS and to the "post-contact force" applied by the ATV during 10 seconds in order to activate the docking system. With the considered ISS and ATV configurations, the global effect has been estimated to a maximal impulse of ± 0.08 °/s on the pitch axis and ± 0.08 °/s on the yaw axis.

The ISS attitude is determined by the initial conditions and the equation of dynamics:

$$I\cdot\frac{d\vec{\Omega}}{dt}+\vec{\Omega}\otimes I\cdot\vec{\Omega}=\vec{T} \quad (1)$$

where I is the inertia tensor, T is the applied torque and Ω is the angular rate with respect to an inertial frame.

Thanks to Monte-Carlo simulations during 110 minutes, it can be observed that the maximal angular rate is 0.22 °/s (with maximal rates per axis close to 0.2 °/s) and that **any attitude can be reached** in less than 110

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minutes. Even in 20 minutes, most attitudes can be reached, as it can be seen on Fig. 1 that represents the ISS roll angles and the directions of the ISS main axis on the unity sphere (in the local (Vbar, Rbar, Hbar) orbital frame) reached by 1000 simulations at 5, 10 and 20 minutes after the first contact.

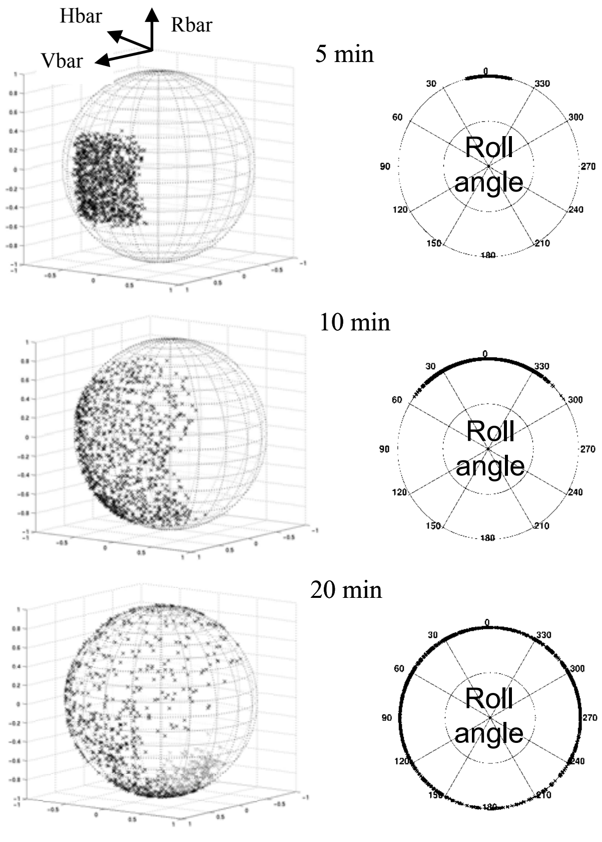

Fig. 1. ISS attitude evolution before departure

1.2 ATV communication with the Ground

The ISS orbit has an inclination of 51.6° and the ISS altitude is always comprised between 350 km and 460 km. The ATV and ATV Control Center (ATVCC), located in Toulouse, communicate via 4 geostationary relay-satellites: Artemis and three Tracking and Data Relay Satellites (TDRS). Therefore, during the attached phase, the communication can be interrupted due to the ISS uncontrolled attitude motion, since the ATV antenna coverage is not omni-directional (half-angle of the transmission aperture cone equal to 80°).

Table 1. Relay-satellites location

Relay-satellite	TDRS-East	TDRS-West	TDRS-Zoe	Artemis
Longitude	41° W	174° W	275° W	-21.5° W
Altitude	35 786 km			

Therefore, in order to know if the Ground could be involved into the elaboration and transmission of the departure operations, we shall estimate the duration of communication availability in the worst cases.

When the ATV probe is captured but not retracted, the ATV main axis can move in a 22.5° half-angle cone, and has a roll degree of freedom of ± 23.5°. To evaluate the communication availability, we consider the worst attitude in the cone but no roll deviation.

With the ISS attitude determined by the 1000 Monte-Carlo simulations described in § 1.1 and considering all possible initial orbital positions at first contact above Russia (since the docking must take place during visibility by the Russian Ground Stations), we obtain the duration of available communication between ATV and ATVCC given in Table 2.

Table 2. Proportion of communication time over 110 minutes

Best case	Mean case	Worst case
91%	48%	0%

This communication availability could be reduced if the masking effects due to the particular geometry of ATV and ISS were taken into account.

In average cases, communication is available not even half of the 110-minutes period, and in the worst cases **no communication at all is possible** during the whole period (in such cases, ATVCC may not even be able to monitor the departure).

1.3 Consequence on the strategy design

If the Ground had to manage the separation and departure operations, it would need communication opportunities satisfying the following constraints:

- total duration long enough for sufficient telemetry and transmission of command plans,
- non-interrupted periods long enough for data consistency and complete plans transmission,
- early communication to let sufficient time for analysis, computation and validation on Ground,
- one remaining opportunity after Ground analysis, for plan transmission before the 110 minutes end.

As said in § 1.2, in the worst cases no communication at all is available. But even when a communication period is available, these constraints are often not satisfied.

Since there is no guarantee that visibility opportunities sufficiently large to perform recovery operations by ground might occur, the separation and departure operations have to be activated by ISS crew through the ISS/ATV link and shall not require Ground involvement.

However, the ISS crew has no possibility to compute and validate itself a safe departure sequence adapted to the current situation and to the actual ISS/ATV attitude. Therefore, **a specific mission plan has to be ready on-board** (and not uploaded by ATVCC) **to be activated by the crew** at any moment, whatever the ISS attitude.

As a consequence, the departure strategy has to be designed in order to impose no constraint on the departure time or on the ISS attitude, be robust to navigation errors and execution dispersions, and allow a **fast and autonomous on-board determination of the command**. To reach this last objective, it has to be designed with simplicity in mind, i.e. minimisation of the number of manoeuvres and parameters which depend on the departure conditions.

2. SEPARATION STRATEGY

In the considered docking contingency case, the ATV probe is only captured by the docking system, but not retracted. In this situation, since the pushers are not compressed, there is no force to extract the probe from the docking mechanism, except ATV thrusters but with a large risk of inability of the ATV Guidance, Navigation and Control (GNC) to execute safely the extraction. As a consequence, a **pyrotechnic separation** is required for more safety:

- after the pyrotechnic separation, the probe will stay locked in the ISS and the rest of the ATV will have the possibility to escape,
- there is no risk to have the catastrophic case where the ATV is attached by the probe and runs a fly-away manoeuvre,
- the separation is clean: there is no debris jettisoned, no induced movement on the ATV and therefore no interaction with ATV GNC,
- the separation date is not ambiguous: it corresponds to the pyro firing.

However, it must be ensured that no unexpected initiation of the sequence can occur. Therefore, the sequence initiation will require from the ISS crew to send two successive commands of two different types (for initiation and confirmation):

- first step: a specific plan jump command is sent by the crew from the laptop. This plan jump is authorised only if the ATV is in a "docking in progress" mode (protection for nominal departure flights),
- then ATV checks-up its configuration (GNC and propulsion) and sends a readiness confirmation to the crew,
- second step: ATV waits for a "GO" command from the crew before starting the pyro separation.

After separation, the crew can not intervene anymore (the other emergency manoeuvres commands given to the crew are inhibited because they may be dangerous in this particular configuration).

3. DEPARTURE STRATEGY

3.1 Safety objectives

One of the main concerns of the departure strategy is to ensure safe trajectories: all possible ATV trajectories including GNC and manoeuvre execution dispersions must be safe with respect to collision with ISS during 24 hours. Some safety criteria have been defined to guarantee this objective:

- the distance between the ATV and ISS centres of mass must increase continuously at least until a distance of 1000 m,
- after the 1000 m distance is reached, the ATV shall never come back at a distance closer than 1000 m during 24 hours after departure.

These two criteria are translated into a simple criterion:

$$\boldsymbol{dmin > 1000\ m} \qquad (2)$$

if *dmin* is defined as the minimum distance reached by the ATV when the distance *d* is decreasing, as illustrated on Fig. 2.

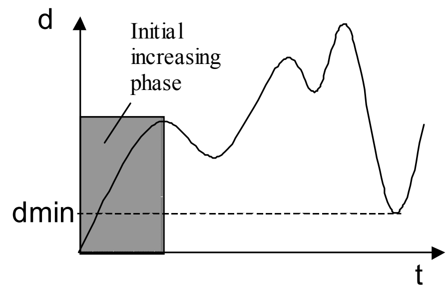

Fig. 2. Illustration of the *dmin* definition

The same definition can be applied on another safety coefficient *k* related to an ellipsoid centred on the ISS and denoted Approach Ellipsoid, with a semi-major axis equal to 2000 m (along Vbar axis), and semi-minor axes equal to 1000 m (on Rbar and Hbar axes). The *k* coefficient is defined as follows:

$$k = \sqrt{\frac{x^2}{2000^2} + \frac{y^2 + z^2}{1000^2}} \qquad (3)$$

where x, y and z are the ATV position co-ordinates in meters in the (Vbar, Rbar, Hbar) ISS frame. This definition implies that $k < 1$ when the ATV is inside the ellipsoid, $k > 1$ when it is outside and $k = 1$ on the boundary.

By analogy with the *dmin* distance criterion (Eqn. 2), we define an additional safety criterion:

$$\boldsymbol{kmin > 1} \qquad (4)$$

where *kmin* is the minimum *k* value reached by the ATV when *k* is decreasing, as illustrated for *dmin* on Fig. 2. This criterion means that:

- first, when still inside the Approach Ellipsoid, the ATV must get continuously closer to its borderline,
- then, after it has gone outside, the ATV shall not come back into the ellipsoid during 24 hours.

The Approach Ellipsoid includes the sphere of radius 1000 m; however the *dmin* criterion has been kept in order to ensure a positive range derivative up to 1000 m.

These forbidden volumes do not represent the physical size of the Station, which is lower than 100 m, but only system margins for robustness.

3.2 Sequence of manoeuvres

In spite of the failed docking, ATV on board functions and resources are nominal, i.e. in health status that would allow a nominal departure, except the fact that the initial attitude can be very far from LVLH.

The departure sequence of manoeuvres begins right after the pyrotechnic separation. This sequence, simple and **totally pre-computed at departure time**, is composed of:

- a 1st boost of fixed amplitude and pre-computed orientation given by the ATV attitude at departure time,
- a free drift phase of fixed duration which includes a pre-defined attitude manoeuvre,
- a 2nd boost of fixed amplitude, fixed direction but with a variable sign pre-selected at departure time, depending on ATV attitude.

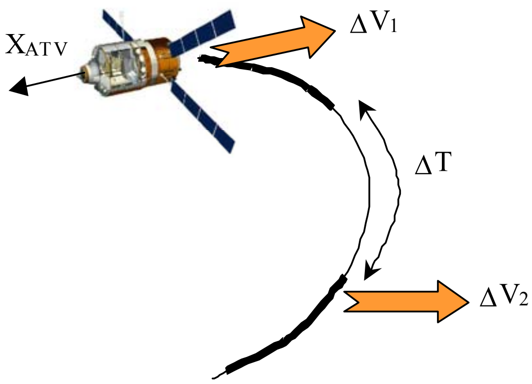

Fig. 3. Departure sequence of manoeuvres

The only parameters of the sequence that depend on the initial conditions are the boosts orientations, which are autonomously selected by the GNC at departure time:

- the 1st one is opposite to the initial orientation of the ATV main axis X_{ATV},
- the 2nd one is purely along +Vbar or –Vbar, the selection being done in order to have the same sign on Vbar axis than the 1st boost.

In other words, the 2nd boost depends on the location of the ATV main axis X_{ATV} at departure time. Two half-spaces separated by the plane perpendicular to Vbar can be identified (see Fig. 4): if X_{ATV} is in the half-space containing +Vbar (respectively -Vbar), the 2nd boost will be along -Vbar (respectively +Vbar).

Due to attitude estimation errors and to the 1st boost execution inaccuracy, it can occur in a few cases that the sign of the 2nd boost is not selected correctly. This can occur only when X_{ATV} is very close to the boundary plane perpendicular to Vbar, which means that the Vbar component of the 1st boost is very small.

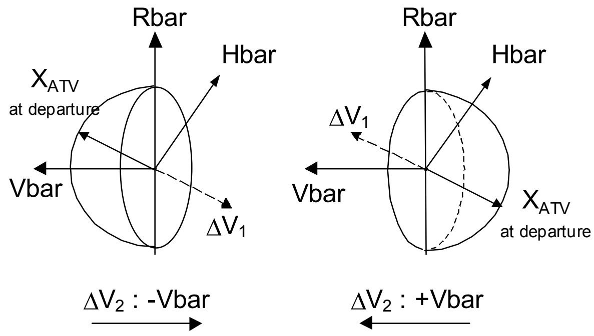

Fig. 4. Selection of the 2nd boost sign

The amplitude of both boosts is fixed at 2 m/s (as for the unique boost of a nominal departure) and the free drift duration is equal to 21 minutes. These values result from a compromise between the maximisation of the safety margin and the maximisation of the time margin for preparation of the 2nd manoeuvre. They could be modified in order to increase one of these margins while decreasing the other.

Both boosts are performed with the Attitude Control System (ACS) thrusters, which allow a thrust in any direction whatever the ATV attitude. The nominal thrust level is 150 N, which gives a duration comprised between 160 s and 270 s for each boost (for an ATV mass comprised between 12 and 20.2 tons).

The ATV attitude is controlled by the GNC during the whole sequence. During the 1st boost, the commanded attitude is the initial attitude at departure time (and therefore opposite to the commanded boost orientation). If the current attitude differs from the commanded one (for instance due to an initial angular rate), the thrust is however executed in the commanded direction by the ACS thrusters and the GNC will make the ATV attitude converge towards the commanded one. During the first part of the free drift phase, a slew manoeuvre is performed towards a so-called Yaw Steering attitude, corresponding to the optimal attitude with respect to

Sun lighting of the solar arrays, for maximisation of electrical power. This attitude varies slowly with time, with a period of one revolution. During the second part of the free drift phase, during the 2nd boost and still after the boost, the ATV attitude follows the Yaw Steering attitude. This attitude ensures that the Star Trackers are available, while it may have not been the case during the 1st boost and the slew (Star Trackers may have been dazzled by the Sun or by the Earth, or masked by the ISS). The Star Trackers recovery improves the attitude navigation and therefore the execution accuracy of the 2nd boost. However, if the Star Trackers were not available for some reason, the attitude navigation with the only gyrometers would be sufficient to perform the 2nd boost safely.

The slew manoeuvre towards Yaw Steering attitude can last up to 11 minutes if it is equal to 180°. In such a case, 10 minutes remain to recover the Star Trackers and to let the attitude navigation filter converge before the 2nd boost, operation that requires only about 3 minutes, which gives a time margin of about 7 minutes for robustness. Since the slew manoeuvre puts the ATV into an attitude that allows the recovery of communication with the Ground, the time margin after this slew manoeuvre will be useful for the ATVCC to check if the ATV status, trajectory and manoeuvre plan are satisfactory before execution of the 2nd boost.

The departure timeline is given on Fig. 5 in the case where the ATV has the maximal mass of 20200 kg and where the slew has the maximal duration.

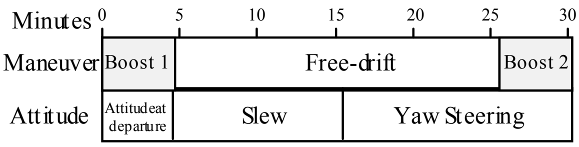

Fig. 5. Departure timeline

After the second boost, the ATV is on a long term safe orbit and will wait there (possibly up to 24 hours) for the ATVCC to plan the end of the mission and the deorbitation.

3.3 Safety analysis of the trajectories

Departure trajectories have to be assessed in terms of safety with respect to collision with ISS through the safety criteria on *dmin* and *kmin* defined in § 3.1. One thousand trajectories have been simulated by the Monte-Carlo method, with random selection of the initial attitude at departure time, of the ISS initial angular rate (that gives an initial velocity up to 0.175 m/s to the ATV), of the ATV attitude estimation error and of the boosts execution dispersions. The initial attitude is considered as equiprobable among all directions and the other parameters are selected according to normal laws within maximal values at 3σ (99.73% of probability) that are given in Table 3.

Table 3. Maximal dispersions at 3σ

ISS angular rate at separation		± 0.3°/s
ATV attitude estimation error		± 9.5°
Boosts execution dispersions	amplitude	± 10%
	orientation	± 5.7°

The performance of attitude estimation considered in Table 3 is compatible with a departure at the latest (110 minutes after the first contact) with a navigation based on the only gyrometers with no attitude update by the Star Trackers during the attached phase, since they can be dazzled by the Sun, the Earth or the ISS. However, if the departure occurred earlier than 110 minutes, the attitude navigation performance would be better because the gyrometers would have drifted during less time.

With these hypotheses, **the safety criteria** on *dmin* and *kmin* (Eqns. 2 and 4) **are satisfied by the 1000 simulated trajectories**, and the worst cases are reported in Table 4.

Table 4. Worst safety coefficients (1000 trajectories)

Coefficient	Worst case	Criterion
dmin	1330 m	> 1000 m OK
kmin	1.23	> 1.00 OK

The trajectory corresponding to the minimal value of the *kmin* coefficient (*kmin* = 1.23) is illustrated on Fig. 6 with respect to the Approach Ellipsoid during the first hour after separation. On this figure, boost phases are represented by a larger line.

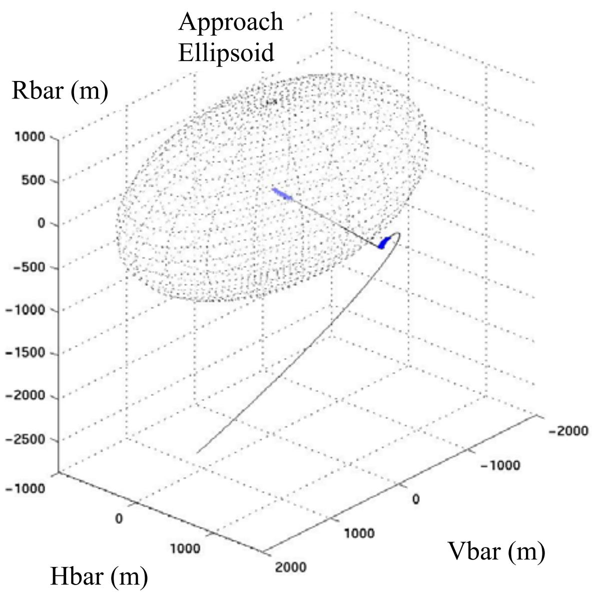

Fig. 6. Trajectory with the lowest *kmin* coefficient

The evolution of the *k* coefficient along this trajectory is represented on Fig. 7 for short term (during 1 hour) and on Fig. 8 for long term (during 24 hours). On Fig. 7, boost phases are still represented by a larger line.

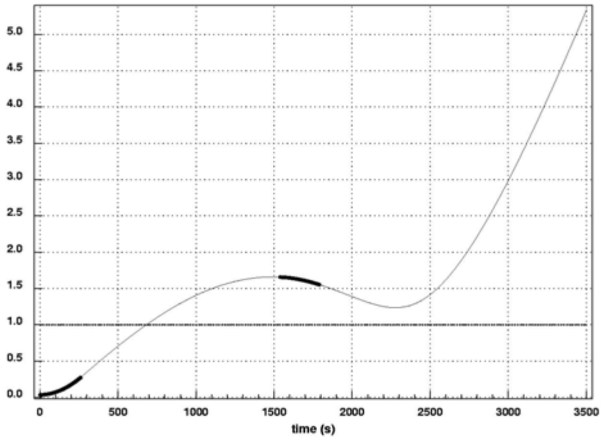

Fig. 7. Safety coefficient *k* at short term (1 hour)

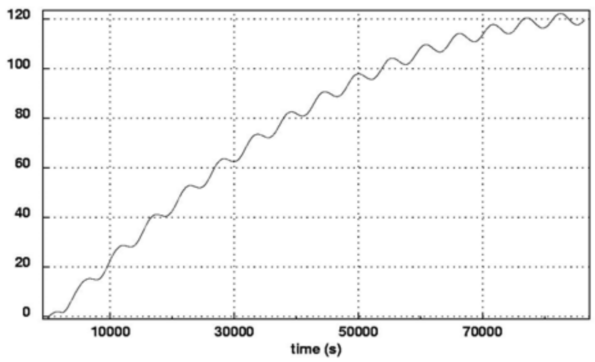

Fig. 8. Safety coefficient *k* at long term (24 hours)

This worst case trajectory corresponds to a first boost almost purely out-of-plane (initial ATV attitude at separation close to Hbar). If only the first boost existed, the ATV relative trajectory would remain purely out-of-plane and oscillate around the ISS position with a period equal to the orbital period and there would be a risk of collision with the ISS 45-50 minutes after separation. But a second boost is initiated right after the ATV has reached its maximum distance from the ISS. The safety coefficients decrease for a while during this second boost integration and thus reach their minimum value while the ATV is still at more than 1300 m from the ISS. After the second boost, the ATV is on a safe orbit at long term, leading after 24 hours to a distance between 200 km and 1500 km from the ISS, depending on the 1st boost orientation. The stabilisation of the *k* coefficient at the end of the 24 hours that can be seen on Fig. 8 is due to the integration effect of the ATV and ISS different air drags that tend to bring the ATV orbit closer to the ISS one in this case.

As stated in § 3.2, the duration between both boosts is equal to 21 minutes, which leaves a margin of about 7 minutes. A reduction of this time margin by 3 minutes would increase the safety margin by about + 200 m on *dmin* and + 0.2 on *kmin*. But with the probability level considered here (1000 simulations) it appears not to be useful, the safety distance being already larger than 1300 m (and this allows to let more time to ATVCC after communication recovery to check the ATV status, trajectory and manoeuvre plan before execution of the 2nd boost).

4. CONCLUSION

The elaboration of this separation and departure strategy has consisted in a complete system design loop involving many disciplines such as mission analysis, communications, on-board software, procedures and operations.

Finally, the presented scenario is simple, safe, robust, automatically managed by the ATV on-board software (after a GO given by the ISS crew) and applicable in any initial ISS attitude.

Beyond the specific case of unsuccessful docking, this departure strategy can also be used for any other ISS contingency leading to a similar situation and could be applied to other vehicles/docking ports configurations.